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Enhancing Shoulder Joint Health Monitoring: A Novel Approach to Acoustic Emission Recording Device

Abstract. Assessing the human shoulder joint is crucial in orthopedics and rehabilitation, especially for issues related to aging or trauma. Traditional diagnostic methods like radiography and MRI are expensive and require specialized facilities. This work presents a new non-invasive, cost-effecitve, and portable device for capturing acoustic signals from shoulder joint, allowing synchronous recording from four areas on the skin surface. The device offers potential for accessible diagnostics, despite the need for a quiet environment during assessment.

*Streszczenie. Ocena ludzkiego stawu barkowego ma kluczowe znaczenie w ortopedii i rehabilitacji, zwłaszcza w kwestiach związanych ze starzeniem się lub urazami. Metody diagnostyczne, takie jak radiografia i rezonans magnetyczny, są drogie i wymagają specjalistycznych urządzeń. Niniejsza praca przedstawia nowe, nieinwazyjne, niedrogie i przenosne urządzenie do rejestracji sygnałów akustycznych z czterech obszarów na powierzchni skóry. Urządzenie oferuje potencjał w zakresie dostępnej diagnostyki, pomimo potrzeby cichego otoczenia podczas oceny. (**Lepsze monitorowanie stanu stawu barkowego: Nowe podejscie do urządzenia rejestrującego emisję a**kustyczną)*

Keywords: acoustic emission recording, shoulder joint, joint surface evaluation
Słowa kluczowe: rejestracja emisji akustycznej, staw barkowy, ocena powierzchni stawu

Introduction

Physical activity stands as a fundamental aspect of daily life, contributing significantly to both physical and psychological well-being when appropriately balanced[1, 2]. Within the human musculoskeletal system – comprising the skeletal and muscular systems – joints play a pivotal role as essential connectors between bones, allowing for a diverse range of movements [3, 4]. The shoulder joint, particularly, holds indispensable significance in fostering independent living by facilitating hand movements, crucial for precise and robust performances such as lifting, moving, pressing, and setting objects down.

Shoulders within the human skeletal structure represent intricate compositions, which incorporate tendons, ligaments, menisci, joint capsules, and cartilage. These components play a vital role in connecting the shoulder girdle and ensuring the proper alignment of articular surfaces, thereby enabling crucial movements like lifting-lowering, adduction abduction, and rotational actions [5]. Given the considerable loads they support, shoulders are susceptible to injury, necessitating diagnostic assessments that encompass various methods such as radiography scans (X-rays), ultrasound imaging (USG), computed tomography (CT), magnetic resonance imaging (MRI), and arthroscopy [6]. The evolution of sensor technology, characterized by enhanced complexity, precision, and sensitivity, has paved the way for the development of more accessible and cost-effective devices to evaluate the condition of human joints. Among these approaches, Acoustic Emission Analysis (AEA) emerges as a prominent method, chosen by the authors for further exploration [7, 8, 9, 10]. Recent research by Schlüter et al. has identified potential biomarkers for osteoarthritis (OA) through high-frequency AEA during knee movements under load8,10. These findings are promising in delineating a confluence of structural changes and joint stress factors, which can extend beyond the knee joint to encompass other articulations.

The main objective of this study was to design an affordable and portable device to assess human joint conditions with the capability to capture acoustic signals from multiple areas within a single joint simultaneously

Materials and Methods

Device design

For the purpose of designing a device to measure acoustic emissions in shoulder joints, all necessary components were gathered for its construction. The device encompasses key elements: a sound card, microphones, power supply, cables, and connectors. Subsequent subsections will provide detailed descriptions of each main element, outlining their specific features and contributions to the device's overall functionality.

Sound card

The sound card holds a pivotal role as a fundamental component within the device, tasked with converting detected audio signals from analog to digital format. Choosing a high quality sound card was crucial to ensure precise and reliable data recording while also maintaining the device's cost effectiveness. In aiming to maximize usability, the authors opted for a sound card compatible with USB ports in most computers, expanding its applicability. After thorough market research, the Focusrite Clarett 4Pre USB (Focusrite Audio Engineering Limited) emerged as the optimal choice for this project.

Several factors informed this decision. Firstly, the Focusrite offers a user-friendly application interface, streamlining setup and improving the overall user experience. Its potential for future development is promising, enabling further advancements without necessitating a change in the sound supplier. Moreover, the sound card's parameters surpassed the requirements for the intended purposes. Below, the essential parameters of the sound card are presented [11]:

- Inputs 18: analogue (8), S/PDIF (2), ADAT (8), • Mixer Fully assignable 26-in/10-out mixer,
- Custom mixes 10 mono,
- Maximum custom mix inputs 18 mono,
- Supported sample rates 44.1 kHz, 48 kHz, 88.2 kHz, 96 kHz, 176.4 kHz, 192 kHz,
- Microphone Inputs:
  - – Frequency Response 20 Hz - 35 kHz ±0.5 dB at minimum gain,
  - – Dynamic Range 118 dB,
  - – THD+N 0.0009%,
  - – Noise EIN ±128 dB (A-weighted),
  - – Maximum input level +18 dBu at minimum gain,
  - – Gain Range 57 dB.

Microphones

Microphones are crucial components of devices for acoustic emission recording. They capture the acoustic signals emitted by joints during movement. The selection of suitable microphones is critical to ensure optimal sensitivity and accuracy in signal recording. It is imperative for the micro PRZEGL ˛AD ELEKTROTECHNICZNY, ISSN 0033-2097, 1 phones to detect signals within the audible range of 20Hz to 20kHz. Balancing performance and cost-effectiveness, electret microphones were chosen for their favorable dimensions, directional signal reception, and reliability. The selected microphone model for the device is the MAX9814 (Maxim Integrated Products), precisely meeting the specific requirements. Below are the essential parameters of the MAX9814 microphone [12]:

- Automatic Gain Control (AGC),
- Three Gain Settings (40dB, 50dB, 60dB),
- 2.7V to 5.5V Supply Voltage Range,
- Frequency range: 20 Hz - 20 kHz,
- Low Input-Referred Noise Density of 30 nV/sqrt(Hz)
- Low THD: 0.04% (typ),
- Low-Power Shutdown Mode,
- Internal Low-Noise Microphone Bias, 2V,
- -40oC to +85oC Extended Temperature Range.

Power supply

An uninterrupted and stable power supply is essential for the continuous and reliable operation of the device. The authors meticulously selected an appropriate power supply to meet the diverse energy requirements of the components, which are as follows:

- Microphones are powered by a two AA battery basket, providing a total power supply of 3V, sufficient for stable operation of the acoustic sensors.
- The USB sound card draws power from the 220V mains using the supplied power adapter. This power source ensures the proper functioning and data processing of the sound card.

To prevent any potential signal distortion, it was imperative to deliberately separate the power supply of the sound card from that of the microphones. This deliberate approach ensures independent operation of each component, optimizing signal recording and overall device performance. The objective behind this separation is to uphold signal integrity and accuracy throughout the recording process.

After the selection of the core elements of the device was finalized, the subsequent phase involved integrating them into a cohesive structure. This was achieved by employing specialized acoustic cables capable of precisely transmitting designated signals. These cables were crafted with a synthetic and rubber anti-interference coating, ensuring dependable signal transmission. During assembly, each connection was isolated using heat shrink tubing to enhance protection. Connectivity was facilitated by employing 6.3mm jack connectors at the cable ends, enabling seamless connections between the sound card and microphones. For power distribution, 2x0.5mm2 copper wires were utilized to supply power to all sensors, linking them to the battery box.

In an effort to maintain cable organization, the authors paired sound and power cables, linking them to individual microphones. Additionally, specialized sockets made of dense sponge were made to cover each microphone. This not only enhanced the device's operational ease but also shielded the sensors' electrical components, preventing direct contact with the patient's skin. The finalized device, depicted in Fig. 1, shows the successful amalgamation of all components into a cohesive and functional design.

Joint examination

Following the completion of the preliminary procedures, the strategic placement of the microphones around the shoulder joint became the subsequent focus. These placements were intended to cover all sides of the joint while maximizing the proximity to the cartilage surface. Additionally, these positions needed to be easily identifiable for subjects of varying ages, heights, and weights which will be helpful in further examinations. Specifically, the microphones were placed methodically in the following areas:

- The lowest point of the acromion,
- Coracoid process of the scapula (processus coracoideus),
- A point situated 8 cm below the coracoid process of the scapula, along the joint space,
- Inferior angle of the scapula (angulus inferior).

All selected detection points are shown in Fig. 2.

Fig. 1. Device designed and developed by the authors for acoustic emission acquisition of the shoulder joint [13]

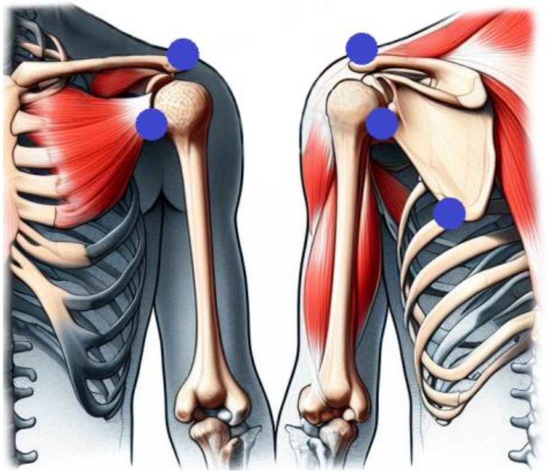


Fig. 2. Selected detection points around the shoulder joint [13]

It is important to note that the last point is not in immediate proximity to the cartilage surface. However, during discussions with an orthopedist, an intriguing idea emerged to explore how the flat and broad bone structure of the scapula transmits sound from the joint.

Evaluation of the device

To facilitate the test, microphones were affixed on the subject to the specified locations, as detailed in the previous subsection. Kinesiology tape was utilized to securely fasten the microphones to the skin, thereby preventing signal contamination arising from potential rubbing sounds between the microphones' sponge and the skin surface. Kinesiology 2 PRZEGL ˛AD ELEKTROTECHNICZNY, ISSN 0033-2097, tape is made to be used directly on the skin for a long time (more than a week), making it safe and durable enough to use during the test. Fig. 3 shows the testing station and Fig. 4 presents a visual depiction of the microphone placements on the shoulder joint during the conducted test.

For the recording process we used the REAPER application (Cockos Incorporated), which is a comprehensive application for computers, including a toolkit for multitrack audio recording, editing and processing. A wide variety of devices, digital formats, and plugins are supported by REAPER [14]. Throughout the recording process using the signals were monitored within the application window. Following the completion of recording, the resulting sounds from the shoulder joint area were displayed on the screen with the possibility of reproduction through the speakers. These variable sounds provided significant information on the condition of the shoulder joint.

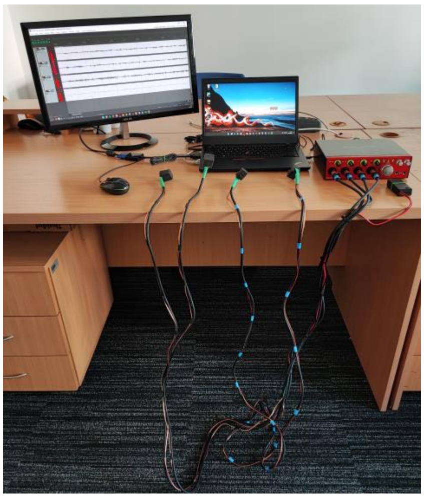
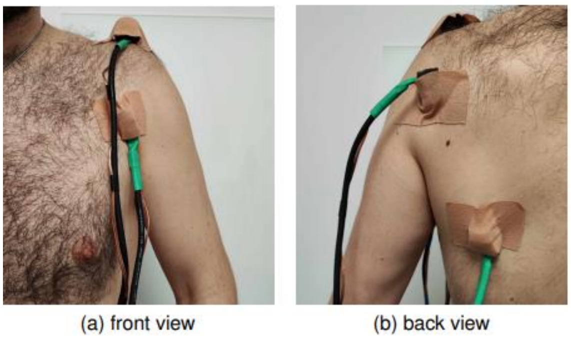


Fig. 3. Testing station



(a) front view

(b) back view

Fig. 4. Microphones placement during examination

During the examination, the subject executed a series of simple exercises involving deliberate arm movements in the shoulder joint:

- Lifting and lowering in the frontal plane,
- Raising and lowering in the sagittal plane,
- Adduction and abduction in the transverse plane.

These movements were executed with the entire arm being carried away to relieve the load from the shoulder joint, allowing the capture of acoustic signals corresponding to various angles and movements of the shoulder bend. This yielded invaluable data for further analysis.

Special attention was paid to maintaining a noise-free environment in the testing room. All noise-producing devices were turned off and the volunteer was positioned at a distance from electronic structures or objects that could impede free movements. These precautions aimed to prevent external noise or interference, ensuring the recorded signals accuracy and reliability in the assessment.

Results

In this section, the authors present the findings from tests conducted using their developed device. Fig. 5 illustrates the recorded signal from a subject, displaying 4 channels of acoustic signals captured by the microphones around the skin surface of the shoulder. The subject involved in this examination was a vibrant 40-year-old male, recognized for his active lifestyle as an enthusiastic swimmer, maintaining robust health and energy. Before the examination the subject gave his informed consent to participate in the study

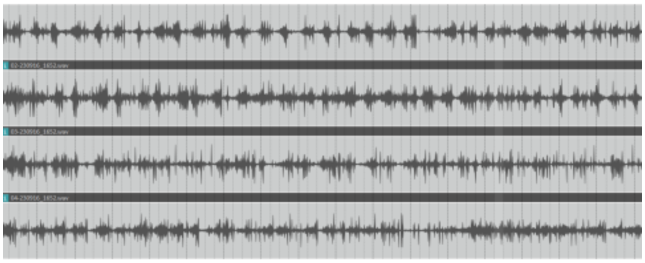


Fig. 5. Device designed and developed by the authors for acoustic emission acquisition of the shoulder joint

Each channel represents signal received from another point from shoulder joint area:

- Channel 1 - A point situated 8 cm below the coracoid process of the scapula, along the joint space,
- Channel 2 - Coracoid process of the scapula,
- Channel 3 - The lowest point of the acromion,
- Channel 4 - Inferior angle of the scapula.

When analyzing the waveforms of the recorded signals, it becomes apparent that the device accurately captured the signals. Each signal maintains a consistent length, with sound volume variations corresponding to specific positions. An interesting observation is the varying amplitude of these changes, indicating distinct microphone positioning and differing distances between the microphones and the cartilage surface. Moreover, variations in signal strength occur when multiple joint elements are engaged on each side of the joint. This dynamic signal strength unveils the intricate nature of the joint's structure, offering valuable insights into the interaction among various joint components during movements and weight-bearing activities.

Discussion

We have successfully developed a portable, economical device capable of capturing a four-channel acoustic signal generated by shoulder movements. To confirm its functionality, we carried out tests utilizing the REAPER application to capture the signals from participants. This versatile device accommodates joint examinations with or without loads. Its compact sensor dimensions and mobility extend its diagnostic capabilities widely. Additionally, its comfort, ease of application, and mobility allow patients to conduct examinations conveniently at home. In addition, it offers a cost-effective alternative to pricier imaging techniques.

However, the construction of the shoulder joint makes its acoustic signals susceptible to interference. To mitigate this, we propose enveloping the device's components (elastic tapes and microphones) with more adhesive material, like silicone strips. This measure aims to minimize skin contact and noise generation from rubbing. During tests, maintaining a relatively noise-free environment is pivotal, necessitating the avoidance of disturbances such as talking or moving furniture. Although the device includes a protective foam coat on the microphones to counter environmental interference, its efficacy in noisy settings remains untested.

It is essential to note that each recorded signal is unique to the individual. Despite similarities in signal and spectrum, data collected and processed from an individual's left and right shoulder joints differ. This device holds considerable potential for orthopedists and physical therapists, aiding in comparing patient groups—spanning from injuries and joint abnormalities to post-joint reconstruction and athletes. Its distinctive examination technique sets it apart from previous studies like Whittingslow et al., who evaluated knee joints using a single sound sensor, and our earlier work employing two sensors simultaneously [9, 10]. Feng et al. utilized advanced piezoelectric film sensors, increasing device costs [15]. On the contrary, our device capitalizes on inexpensive and readily available microphones.

Future efforts should emphasize expanding knowledge and signal diversity to augment the device's diagnostic prowess across diverse patient groups with varying medical conditions. Additionally, plans are underway to increase the sensor count to develop a microphone array for joint mapping and integrate gyroscopes to measure joint angles during examinations. This proposed approach stands to become a valuable diagnostic aid, complementing early-stage medical diagnoses.

Conclusions

The primary objective of this project was to develop a sophisticated device capable of analyzing acoustic signals to assess the condition of the articular surfaces of the human shoulder joint. Meticulously designed, the device utilized specific electronic components, making it simple, cost-effective, and user-friendly. Overcoming initial connectivity challenges ensured that subsequent usage was streamlined and hassle free.

Throughout its development and post-production, precise testing procedures were conducted, facilitating seamless maintenance and highlighting the device's broad spectrum of potential applications. Beyond its diagnostic utility, the device proved invaluable in diagnosing or assessing the rehabilitation progress of the targeted joint.

A notable breakthrough lay in the device's capability to simultaneously and synchronously record signals from four distinct areas, an unprecedented achievement. The project holds promise for further expansion, contemplating additional functionalities and enhancements, such as incorporating hydrophones or leveraging more precise sound cards. Moreover, it exhibits potential for application in examining other major joints.

Future research endeavors are poised to concentrate on advancing the device's capabilities and broadening the scope of experimental subjects, drawing insights from specialized healthcare facilities specializing in orthopedics and rehabilitation. Furthermore, the aim is to juxtapose the outcomes of our device against established imaging modalities like USG, CT, and MRI [16, 17, 18]. This effort aims to refine the testing process, identifying an optimal algorithm to derive valuable analysis from shoulder joint signals.

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